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Description

Pharmaceutical preparation for hearing impairment

Technical Field

The present invention relates to a pharmaceutical preparation for hearing impairment, which is preferable as an agent for preventing, treating or ameliorating hearing impairment such as deafness, used in gene therapy etc.

Background Art

Hearing impairment is the most prevalent sensory deficit of human beings, and are said to occur in at least one of ten persons. Hearing impairment can be caused by a variety of factors including ototoxic substances such as aminoglicoside antibiotics or cisplatin (CDDP), noise and ageing.

These factors affect the inner ear hair cells in the organ of Corti which function as sensory cells that collect and transfer auditory signals to the brain via the auditory neurons. Moreover, degeneration of the auditory nerve occurs secondary to the loss of the sensory hair cells, thus exacerbating the functional impairment of hearing.

In general, hair cells and auditory neurons in mammalian vertebrates have no capacity for postembryonic cellular mitosis to generate new hair cells and neurons. In the mammalian stato-acoustic epithelia, a low level of regeneration is possible for the vestibular receptors *in vivo*. However, no regeneration

of auditory sensory epithelium was observed *in vivo*, except a very restricted regeneration observed in neonatal mouse cochlear *in vitro*.

For the treatment of severely **deaf** ears, the cochlear implant has provided great benefits to patients and has been shown to provide an effective intervention. However, the benefit of cochlear prosthesis depends on the quality and quantity of the auditory nerve population, and their loss severely compromises the hearing benefits it provides.

The past studies show a clear relationship between the total number of viable auditory neurons available for stimulation and the performance of subjects receiving cochlear implants. This shows that the implant cannot always produce satisfactory results.

It is therefore necessary to develop the therapeutic strategy of preserving or regenerating the auditory neurons to increase the effectiveness of the implant. Recent studies revealed that multiple neurotrophic factors such as nerve growth factor (NGF), glial cell line-derived neurotrophic factor (GDNF), brain-derived neurotrophic factor (BDNF), neurotrophic factor-3 or NT-4/5 have been shown to have effects on the survival of inner ear auditory neurons, including spiral ganglion cells (SGCs).

A prior art relevant to the present invention, that is, US-A 6,136,785 discloses a method of protecting sensory hair cells in the inner ear against damage caused by ototoxic substances such as aminoglicoside, which comprises

administering a growth factor or a mixture thereof into a vertebrate. As its relevant prior arts, WO-A 98/00014, US-A 6,017,886, JP-A 2002-503687 etc. are also known.

Disclosure of the Invention

The object of the present invention is to provide a pharmaceutical preparation for hearing impairment, which can prevent or treat hearing impairment by preserving or regenerating the auditory neurons.

The present inventors focused attention on the fact that a hepatocyte growth factor (HGF) gene is a therapeutic substance effective for curing hearing impairment, and they conducted extensive study to complete the present invention.

As a means for solving the problem, the invention in claim 1 provides a pharmaceutical preparation for hearing impairment, which comprises a hepatocyte growth factor (HGF) gene as an active ingredient.

As another means for solving the problem, the invention in claim 2 provides a pharmaceutical preparation for hearing impairment, which comprises a plasmid of a hepatocyte growth factor (HGF) gene as an active ingredient.

As another means for solving the problem, the invention in claim 3 provides a pharmaceutical preparation for hearing impairment, which comprises a virus envelope vector encapsulating a hepatocyte growth factor (HGF) gene or its plasmid as an active ingredient.

As another means for solving the problem, the invention

in claim 4 provides the pharmaceutical preparation for hearing impairment according to claim 3, wherein the virus is one member selected from the group consisting of Sendai virus, retrovirus, adenovirus, adeno-associated virus, herpes virus, vaccinia virus, pox virus and influenza virus.

The pharmaceutical preparation for hearing impairment according to the present invention is suitable as an agent for preventing hearing impairment or as an agent for treating or ameliorating hearing impairment, and is particularly suitable as a pharmaceutical preparation for genetic therapy for deafness.

The present invention provides use of a hepatocyte growth factor (HGF) gene or a plasmid of a hepatocyte growth factor (HGF) gene for producing a pharmaceutical preparation for hearing impairment, as well as a method of treating hearing impairment, which comprises administering, to a patient with hearing impairment, a hepatocyte growth factor (HGF) gene or a plasmid of a hepatocyte growth factor (HGF) gene in an amount effective for the treatment.

As used herein, the "hepatocyte growth factor (HGF)" is a physiologically active peptide exhibiting various pharmacological actions, represented by SEQ ID NO:1 in the Sequence Listing, and the pharmacological actions are described in, for example, "Jikken Igaku" (Experimental Medicine), Vol. 10, No. 3 (extra issue) 330-339 (1992), and WO-A 97/7824 describes various applications thereof as the prior art, but no pharmacological action thereof on hearing impairment is known.

Detailed Description of the Invention

The hepatocyte growth factor (HGF) gene contained as an active ingredient in the pharmaceutical preparation for hearing impairment according to the present invention refers to a gene capable of expressing HGF, and is specifically represented by SEQ ID NO: 2 in the Sequence List. This gene also encompasses genes consisting of the same gene sequence as above except that the sequence is partially deleted or substituted by other base(s), has another nucleotide sequence inserted into it, or has a base added to the 5'- and/or 3'-end thereof insofar as their expressed polypeptides have substantially the same effect as that of HGF.

As the HGF gene, an HGF gene described in Nature 342, 440 (1989), JP-A 5-111383, WO-A 90/10651, Biochem. Biophys. Res. Commun. 163, 967 (1989) etc. may be used.

The HGF gene can be used in a suitable vector, preferably in a form incorporated in a plasmid.

The HGF gene encapsulating in a virus envelope from which RNA was removed, or a virus envelope vector encapsulating a plasmid containing the HGF gene, can be used as the HGF gene.

The virus used herein may be wild-type virus or recombinant virus. This virus is preferably one member selected from the group consisting of Sendai virus, retrovirus, adenovirus, adeno-associated virus, herpes virus, vaccinia virus, pox virus and influenza virus. Among these viruses, HVJ is more preferable, and particularly inactivated HVJ is preferable. The term "inactivated" means that the genome of the virus is inactivated.

Specifically, Sendai virus for example VR-105, VR-907 etc.

can be purchased from American Type Culture Collection (ATCC), telephone 1-703-365-2700, P.O. Box 1549, Manassas, VA 20108, USA.

http://www.atcc.org/SearchCatalogs/longview.cfm?view=av,152376,VR-105&text=Sendai&max=20

http://www.atcc.org/SearchCatalogs/longview.cfm?view=av,1375478,VR-907&text=Sendai&max=20

As the virus envelope vector, an HVJ envelope vector disclosed in WO-A 01/57204 can be used.

The form of the pharmaceutical preparation for hearing impairment according to the present invention is determined in relationship with the administration method, but in the present invention, the pharmaceutical preparation is formed preferably into an injection.

When the pharmaceutical preparation for hearing impairment according to the present invention is formed into an injection, the injection can be produced by mixing the HGF gene, a plasmid of the HGF gene, or a virus envelope vector encapsulating the hepatocyte growth factor (HGF) gene or the plasmid, with a pharmaceutically acceptable carrier (sterilized water, physiological saline, phosphate buffered physiological saline, a buffer solution, etc.).

If necessary, the carrier can contain a very small amount of additives such as substances enhancing isotonicity and chemical stability. Such substances are used in such an amount and concentration as not to be toxic to the patient.

Such substances include buffering agents such as phosphoric

acid, citric acid, succinic acid, acetic acid and other organic acids or salts thereof; antioxidants such as ascorbic acid; polypeptides with a low-molecular weight (less than about 10 residues) (for example, polyarginine or tripeptide); protein (for example, serum albumin, gelatin, immunoglobulin); hydrophilic polymers (for example, polyvinyl pyrrolidone); amino acid (for example, glycine, glutamic acid, aspartic acid, arginine); monosaccharide, disaccharide and other hydrocarbons (for example, glucose, mannose, sucrose, dextrin, cellulose or its derivatives); chelating agents (for example, EDTA); sugar alcohol (for example, mannitol, sorbitol); counter ion (for example, sodium); nonionic surfactants (for example, polysorbate, poloxamer); polyethylene glycol etc.

When the pharmaceutical preparation for hearing impairment according to the present invention is formed into an injection, the pharmaceutical preparation is stored as a dried product and a diluent respectively, or as an aqueous solution, in a sealed ampoule and vial.

When the pharmaceutical preparation for hearing impairment according to the present invention is administered in the form of e.g. an injection into humans, it is possible to employ a method of direct administration into the inner ear via a cochlea, a method of direct administration into the inner ear via a semicircular duct, a method of administering it into cerebrospinal fluid to carry it to the inner ear, a method of administering it into the middle ear to infiltrate the inner ear, a method of directly administering it into the inner ear

by a device for sticking or gradually releasing it to an inserted electrode, which was integrated in the inner ear upon surgery for implanting the cochlear implant.

The pharmaceutical preparation for hearing impairment according to the present invention is formulated and administered in consideration of the clinical conditions of each patient (for example, conditions to be prevented or treated), the administration method, administration site, administration schedule and other factors known by those skilled in the art, in a mode in accordance with medical implementation standards. Accordingly, the effective amount and suitable administration amount of the pharmaceutical preparation for hearing impairment according to the present invention are determined with such items taken into consideration.

When the pharmaceutical preparation for hearing impairment according to the present invention is administered in the form of a virus envelope vector, the amount of the virus envelope vector administered is usually 0.001 μg to 1 g, preferably 0.01 μg to 500 mg, more preferably 0.1 μg to 100 mg, per kg of patient' body weight.

The amount of the HGF gene in the virus envelope vector administered is usually 0.01 μg to 500 mg, preferably 0.1 μg to 10 mg, more preferably 1 μg to 1 mg, per kg of patient' body weight.

The pharmaceutical preparation for hearing impairment according to the present invention can be used as a medicine for gene therapy of hearing impairment, is suitable as an agent

for preventing, treating or ameliorating hearing impairment, and is suitable as an agent for preventing, treating or ameliorating hearing impairment, particularly deafness.

The present inventors revealed in their study that the injection of HVJ-E encapsulating human HGF into subarachnoid cerebrospinal fluid prevented loss of hair cells and spiral ganglion cells by apoptosis inhibition.

That is, administration of the HGF gene just before treatment with kanamycin can prevent hearing impairment, and can recover auditory functions even after induction of hearing impairment with kanamycin.

These results indicate the significantly outstanding usefulness of HGF gene therapy using the HVJ-E vector.

For transfection of the gene into the inner ear, the following surgical techniques are fundamentally practiced.

i) Direct injection into the cochlea by resection of the cochlea.

ii) Administration via a round window membrane by injection through the membrane or by permeation with a gel containing the vector placed on the intact membrane.

iii) Administration into the inner ear through a posterior semicircular duct by resection.

iv) Administration into an endolymphatic sac.

Up to now, some virus vectors such as adenovirus vector, herpes virus vector and adeno-associated vector have been administered directly into the inner ear by using any one of the 4 techniques described above.

However, the respective techniques have advantages and

disadvantages from the viewpoint of invasive property and effectiveness.

In this study, the present inventors injected the HVJ-E vector into subarachnoid cerebrospinal fluid in order to prevent invasion of the inner ear by direct injection into the cochlea.

By this method, the expression of the introduced gene in the cerebrospinal fluid was confirmed by enzyme activity and immune staining, and no significant damage in the brain or ear tissues was recognized. This fact suggests that after administration into the cerebrospinal fluid, the HVJ-E vector itself reaches spiral ganglion cells in the inner ear, thus indicating some possible pathways from the subarachnoid cerebrospinal fluid into the inner ear.

When the vector was injected into the membrane, no luciferase activity was observed in separate organs, and thus the most possible pathway for the vector to reach from the subarachnoid cerebrospinal fluid to the inner ear is considered to be via a cochlear duct.

If the vector spread via blood stream into the whole body, luciferase activity after intravenous injection would be recognized first in the spleen, and thus expression of the introduced gene should be detected in separate organs such as spleen and lung.

Conventionally, neutrophic factors such as NGF, BDNF, GDNF and NT-3 have been used in treatment of the sense of hearing.

However, HGF has not been used for this purpose. It has been revealed that HGF shows not only an effect on the liver

but also neutrophic activity in hippocampus, cerebral cortex, sensory neurons, motor neurons etc., and this time, the present inventors indicated that human HGF was recognized in both subarachnoid cerebrospinal fluid and spiral ganglion cells, and that the human HGF induced endogenous HGF in rats.

HGF gene therapy in the auditory system is considered to have some advantages over conventional gene therapy utilizing neutrophin.

Further, combined use of an artificial inner ear and HGF gene therapy, that is, the administration of HGF gene during artificial inner ear surgery, would also be effective.

Hearing impairment are accompanied by a loss in hair cells and spiral ganglion cells, and prevention of this loss in the cells is worked out by the protective action of HGF against cell death by apotosis. Expression of HGF is effective in recovery of functions even after induction of hearing impairment by treatment with kanamycin.

Thus, HGF gene therapy is one highly promising method for treatment of hearing impairment in the sensory nerve.

This study provides a new finding and technique for treatment of hearing impairment by a combination of HGF gene and HVJ-E vector transfer system.

The pharmaceutical preparation for hearing impairment according to the present invention is suitable as a pharmaceutical preparation for gene therapy particularly for purposes such as prophylaxis, therapy etc. of deafness.

Brief Description of Drawings

Fig. 1 is a graph showing a change with day in auditory functions in an auditory function test in Examples.

Fig. 2 is a graph showing a change with day in auditory functions in an auditory function test in Examples.

Fig. 3a is a microphotograph of intact spiral ganglion cells, Fig. 3b is a microphotograph of a group treated with kanamycin, and Fig. 3c is a microphotograph of a group treated with kanamycin + HGF.

Fig. 4 is a graph showing the density of spiral ganglion cells in a group treated with kanamycin + HGF and in a group treated with kanamycin + vector.

Fig. 5 is a graph showing the density of spiral ganglion cells in a group treated with kanamycin + HGF and in a group treated with kanamycin.

Examples

Hereinafter, the present invention is described in more detail by reference to Examples, but the present invention is not limited by Examples.

Preparation of plasmid DNA

pCMV-*lac*Z (9.2 kb) was constructed by inserting a *Hin*dIII-*Bam*HI fragment of pSV-β-galactosidase (Promega Corp., Madison, WI, USA) into pcDNA3 (5.4 kb) (Invitrogen, San Diego, CA, USA) at the *Hin*dIII and *Bam*HI sites.

pCMV-luciferase-GL3 (pcLuc-GL3: 7.4 kb) was constructed by cloning the luciferase gene from the pGL3-basic Vector

(Promega) into pcDNA3(Invitrogen).

pVAX1-hHGF (5.2 kb) was constructed by inserting the human HGF cDNA into pVAX1 (3.0kb) (Invitrogen) at the *Bam*HI and *Not*I sites.

Plasmids were purified with the QIAGEN plasmid isolation kit (Qiagen, Hilden, Germany).

Preparation of HVJ-envelope vector

Hemagglutinating virus of Japan (HVJ; Sendai virus) envelope vector (HVJ-E) was constructed by encapsulating plasmid DNA into inactivated HVJ particles according to Example 8 in WO-A 01/27204, except that HVJ was purified by centrifugation and inactivated by irradiation with UV rays.

Preparation of HVJ-E suspension (pharmaceutical preparation for hearing impairment according to the present invention)

UV-inactivated HVJ (Z strain), 10000 hemmaglutinating unit, was mixed with 200 μg of plasmid DNA and 0.3 % Triton X, washed with balanced salt solution (BSS: 137 mM NaCl, 5.4 mM KCl, 10 mM Tris-HCl, pH 7.6), and adjusted in 100 μl with BSS for intrathecal infusion. HVJ-E encapsulating pCMV-*lac*Z, pcLuc-GL3, pVAX1-hHGF, pcDNA3 or pVAX1 plasmid DNA was used in the present examples.

Experimental animals and treatment groups

Sprague-Dawley male rats (6 weeks of age; 200-210 g) with normal Preyer's reflex were obtained from Charles River Japan (Atsugi, Japan). All procedures were conducted in accordance with the guidelines of the Animal Committee of Osaka University.

Animals were divided into five groups: the protection group,

the rescue group, the protection/rescue group, the vector-control group and the no-therapy group. Animals of all groups were bilaterally deafened by aminoglycoside intoxication; kanamycin sulfate (Meiji Seika, Tokyo, Japan) was administered daily by subcutaneous injection (400 mg/kg/day) for 14 consecutive days.

The protection group and the protection/rescue group were intrathecally injected with HVJ-E suspension encapsulating hHGF gene (pVAX1-hHGF) on the first day of the kanamycin treatment.

The vector-control group was administered with HVJ-E suspension encapsulating the control vector (pVAX1) by intrathecal injection in the same way as above.

On the last day of the kanamycin treatment (on the 14th day), the rescue group and the protection/rescue group were injected with HVJ-E encapsulating pVAX1-hHGF.

In addition, HVJ-E encapsulating pCMV-*lac*Z or pcLuc-GL3 was administered to animals for histochemical analyses and luciferase assays.

After this procedure, expression of β-galactosidase was observed 7 days after transfection and luciferase activity was measured 1 day after transfection.

In vivo gene transfer to subarachnoid space

In this study, gene transfer into the cisterna magna using infusion of HVJ-E was employed as *in vivo* gene transfer into the CNS and the inner ear.

For infusion into the subarachnoid space, after animals were anaesthetized with ketamine (Sankyo, Japan) and xylazin

(Bayer), the head of each animal was fixed in the prone position, and the atlanto-occipital membrane was exposed through an occipitocerebral midline incision.

A stainless cannula (27 gauge; Beckton Dikinson) was introduced into cisterna magna (subarachnoid space). After the withdrawal of the cerebrospinal fluid (100 μl) for confirmation of the cannula position and to avoid increased intracerebral pressure, HVJ-E (100 μl) encapsulating marker gene, hHGF gene or control vector was infused at the speed of 50 μl/min.

Afterwards, the animals were placed head down for 30 minutes. All rats showed no weight loss, loss of activity or behavioral change after administration.

Assay for luciferase activity

Rats transfected with luciferase gene were sacrificed under anesthesia 24 hours after transfection. Organs (brain, lung, spleen, liver and cochlear) were harvested and placed individually in FALCON 50 ml tubes.

Luciferase activity was measured with a luciferase assay kit (Promega) as described previously (44 of HVJ-E). Luciferase levels were normalized by determining the protein concentrations of the tissue extracts (44 of HVJ-E). Luciferase units were expressed as relative light units (RLU) per gram of tissue protein.

Enzyme immunoassay for human HGF in cerebrospinal fluid

Cerebrospinal fluid (CSF) (100 μL) from the rats, 5 and 14 days after the injection of HVJ-E encapsulating hHGF gene, was used for the experiments.

The concentration of human HGF and rat HGF in the CSF was determined by enzyme-immunoassay using anti-human and anti-rat HGF antibody according to the manufacturer's manual (Institute of Immunology, Tokyo, Japan).

The antibody against human HGF reacted with only human HGF and not with rat HGF. The antibody against rat HGF reacted with both human and rat HGF.

Reverse transcription polymerase chain reaction

Rats were deeply anesthetized with ether, decapitated, and the temporal bones were placed in cold RNase-free saline. The otic capsule was removed, and whole cochlears were isolated under the dissection microscope. Tissues from the rats were pooled in lysis buffer, homogenized using a homogenizer, and total RNA was isolated using RNeasy Mini Kit (Qiagen). RNA was reverse-transcribed with the SuperScript First-strand Synthesis System for RT-PCR (Invitrogen).

First-strand cDNA was amplified using the specific primers for human HGF and GAPDH: HGF, upstream primer 5'-TTCACAAGCAATCCAGAGGTACGC-3', downstream primer 5'-GAGGGTCAAGAGTATAGCACCATG-3'; GAPDH, upstream primer 5'-TGAAGGTCGGAGTCAACGGA-3', downstream primer 5'-GATGGCATGGACTGTGGTCA-3' (which are SEQ ID NOS: 3, 4, 5 and 6 respectively in the Sequence List).

The PCR conditions were optimized for each set of primers. The PCR reaction mixture contained 5 μl of cDNA, 5 μl of 10xPCR buffer, 4 μl of 2.5mM dNTP, 2.5 μl of 20 pM upper and lower primers, and 1.5U of Taq polymerase, distilled water added to 45 μl.

Thermocycling conditions: HGF, 94°C for 45 s, 70°C for 2 min and 72°C for 2 min; GAPDH, 94°C for 45 s, 58°C for 1 min and 72°C for 2 min.

Evaluation of the auditory function

To evaluate the physiological condition of auditory function, we performed auditory brainstem response (ABR) audiometry.

The ABRs were measured one day prior to the first day of the kanamycin administration to determine the baselines and were again recorded 7,14,21,28 and 56 days from the beginning of the kanamycin treatment.

Prior to each test of auditory function, the animals were anesthetized with an intramuscular injection of a ketamine (50 mg/kg)-xylazine (10 mg/kg) solution. Needle electrodes were placed subcutaneously at the ipsilateral right pinna (reference electrode), the contralateral pinna (ground electrode) and at the vertex (active electrode). All recordings were performed in a sound-proof room with a Nihon-Kohden Neuropack IV (MEM-4104) system.

The potentials were evoked by single-wave 100 μs click sounds (10/s), and these monaural stimuli were delivered to the right ear by loudspeaker. Responses were digitally filtered (bandpass: 50-3000 Hz), amplified and averaged (500 responses).

The auditory threshold and the latency of P1 waves were assessed and calculated by comparison with each pre-study value. The intensity of the stimulus was varied in 2-dB stepwise increments to determine the threshold. Threshold is defined

as the lowest intensity level at which responses could still be recorded in two consecutive trials to confirm response reproductivity. The results are shown in Figs. 1 and 2.

Fig. 1 shows threshold value (dB) from Day 0 to Day 56, and Fig. 2 shows I-wave latent time (mS). In the graph, HGF shows the protection group, the protection/rescue group, and the rescue group, Vec in the graph shows the vector-control group, and KM in the graph shows the non-therapy group.

As is evident from Figs. 1 and 2, the change in the sense of hearing (change in threshold value and I-wave latent time) of the protection group, the protection/rescue group, and the rescue group was slight even after 56 days, while the change in the sense of hearing (change in threshold value and I-wave latent time) of the vector-control group and the non-therapy group was significant.

Fig. 3 shows optical microphotographs of spiral ganglion cell (SGC) of the cochlea (spiral tact): Fig 3a shows that of the intact cochlea; Fig. 3b shows that of the group treated with kanamycin (non-therapy group); and Fig. 3c is that of the group treated with kanamycin + HGF (the protection group, the protection/rescue group and the rescue group).

As is evident from Fig. 3a to Fig. 3c, the spiral ganglion cells in the kanamycin + HGF treatment group was more intact than in the kanamycin treatment group.

Fig. 4 shows the density of spiral ganglion cells (number of cells/10,000 mm^2) in the group treated with kanamycin + HGF (the protection group, the protection/rescue group and the rescue

group) and in the group treated with kanamycin + vector (vector-control group).

Fig. 5 shows the density of spiral ganglion cells (number of cells/10,000 mm^2) in the group treated with kanamycin + HGF (the protection group, the protection/rescue group and the rescue group) and in the group treated with kanamycin (non-therapy group).

As is evident from Figs. 4 and 5, the density of spiral ganglion cells was higher in the kanamycin + HGF treatment group than in the other treatment groups.

The above results are estimated due to preserve or regeneration of auditory neurons by administration of the HVJ-E suspension.